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GLOBAL AIR QUALITY TREKKERS:
Nandi Clean Kitchen Study

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Samantha Dykhuis graduated from Purdue University in May 2020 with a degree in Industrial Engineering. She was a member of the Global Air Quality Trekkers (GAQT) for three years, and served as one of the team's co–project managers for two years. She traveled with the GAQT team to Kenya during the summer of 2019, where she focused primarily on the analysis of carbon monoxide data from several kitchens. She will be starting her career with Deloitte in their technology consulting practice based out of Chicago, IL.

Steph Schiavo is a senior in Environmental and Ecological Engineering at Purdue University and was a member of the Global Air Quality Trekkers for two years. She was one of the team's co–project managers in her junior year, and she traveled to Kenya with the team in May 2019. She plans to pursue her master's degree in Environmental and Ecological Engineering after graduating from Purdue University in December 2020.

Avalin Senefeld is a senior in Chemical Engineering at Purdue University. She has been a part of the Global Air Quality Trekkers (GAQT) team since her freshman year, and currently serves as the project partner liaison for the team. She plans to pursue a career in process engineering. In this article, she describes her experiences collaborating with project partners to reduce indoor air pollution.

INTRODUCTION

Throughout sub-Saharan Africa, the burning of biomass fuels is a primary method of fire production for cooking and heating (Jones et al., 2014). However, the burning of these fuels emits many harmful pollutants, such as carbon monoxide and particulate matter (U.S. Energy Information Administration, 2019). When inhaled over extended periods of time, these pollutants can cause cardiovascular and respiratory illnesses, such as heart attacks, irregular heartbeat, respiratory symptoms (coughing, difficulty breathing, etc.), and overall decreased lung function (U.S. Environmental Protection Agency, 2018). Kenya is one of many African countries that is adversely impacted by indoor air pollution due to the burning of biomass fuels in enclosed and often poorly ventilated kitchens (World Health Organization, 2018). In Kenya in 2016, there were close to 40,000 deaths attributed to household and ambient air pollution, according to the World Health Organization. In Nandi, a county located in Western Kenya, kitchen air pollution produced by the burning of wood is responsible for adverse health effects in women and their children since they spend prolonged periods in the kitchens while cooking and cleaning (Joseph J. Mamlin, MD, personal interview, January 2017). Rather than switching to cleaner fuel alternatives, which have limited availability in Kenya, or using culturally incompatible "clean cookstoves," some women in the Nandi community have chosen to redesign their kitchens. The redesigned "clean kitchens" utilize natural ventilation to reduce the amount of pollutants present during cooking. These clean kitchen modifications include a chimney that stems from their mud stove, a roof vent (small opening at the top of the structure), and additional windows.

AMPATH Kenya, a large health care organization located in Eldoret, Kenya, took notice of this public health issue occurring in rural Kenya, and organized a team to help with the design, funding, and building of clean kitchens in Nandi. As AMPATH has had a longstanding relationship with Purdue University, they reached out to Purdue Engineering to assemble a team to further aid in the design and evaluation of clean kitchens in Nandi. Thus, the Global Air Quality Trekkers (GAQT) team was established in the fall of 2016. While GAQT has established several goals relating to improving the design of clean kitchens, this article will focus on the clean kitchen program evaluation performed by GAQT for AMPATH while in Kenya in 2019. The purpose of this evaluation was to determine whether or not clean kitchens caused a significant reduction in indoor air pollutants in kitchens in Nandi.

METHODOLOGY

To complete the clean kitchen evaluation in Nandi, the team gathered data on air pollutants in three styles of kitchens. The first type of kitchen is a traditional kitchen, which has no natural ventilation modifications. The second type of kitchen is a clean (or modified) kitchen, which has been previously described and will be shown in more detail further into this article. The third type of kitchen was considered semi-modified, as it contained only a subset of the natural ventilation elements present in a fully modified kitchen. It was crucial that this data collection not disturb the regular cooking practices of the Nandi women in order to accurately capture the pollutant concentrations that these women are regularly exposed to. Although there are several harmful substances present in wood smoke that could be measured, the team decided to measure the carbon monoxide (CO) concentrations inside the various styles of kitchens. There are two key reasons this decision was made. First, the carbon monoxide sensors used are small, noninvasive, and do not require any upkeep or maintenance after being initialized and placed inside the kitchens. Second, the concentration of carbon monoxide is proportional to the concentration of the other particles released during the incomplete combustion of wood, which therefore allows us to estimate the concentration of other particles and make direct comparisons of concentrations between the sampled kitchens (Farrar, 2015). Incomplete combustion occurs when insufficient amounts of oxygen are available or when combustion is not 100% efficient. The burning of wood in stoves similar to the ones used in Nandi almost always has an incomplete combustion reaction (Farrar, 2015). Therefore, tracking the concentration of carbon monoxide allows for minimally invasive tracking of the emissions from the stove and allows for comparison of particle concentration among kitchens.

Tracking carbon monoxide emissions must be conducted over a long period of time in order to accurately determine the women's exposure to the gas. To create an accurate portrayal of emissions in the daily lives of Nandi women, the team decided to collect data over a one-week period. This allows for any differences in cooking or emissions between different days of the week to be mitigated. The team placed sensors at two locations in the kitchen. One was placed around where a woman's breathing zone would be located while cooking in order to measure the concentrations of carbon monoxide the kitchen user inhales. A second sensor was placed about a meter away from the first sensor in order to measure the carbon monoxide concentration in a central area of the kitchen. Unfortunately, there was no way to standardize the distance of the sensors from the stove, due to variability in kitchen construction and available space within the kitchens.

The team chose to use EL-USB-CO (Carbon Monoxide Data Logger with USB) sensors from Lascar Electronics (Figure 1) in order to record carbon monoxide levels. The sensors measure carbon monoxide concentration in parts per million (ppm). Measurements were taken every 30 seconds over a one-week period. The sensors measure CO concentrations up to 1,000 ppm, with an accuracy of approximately ± 7 ppm.

Figure 1. Lascar EL-USB-CO sensor used to collect CO concentration data in Nandi kitchens.

Kitchen Classifications

In order to conduct the kitchen evaluation process, the team selected five kitchens to analyze in Nandi County. To compare each kitchen, the team further classified them into one of the following categories: traditional, semi-modified, or modified (clean kitchen). The traditional kitchens consist of a thatched or iron sheet roof with minimal or small windows, with no chimney, and with no roof vent. The semi-modified category includes kitchens that offer minimal modifications that could include some, but not all, of the following: roof vent, chimney, and enlarged windows. Modified kitchens employ all of the previously listed ventilation strategies, although the number and size of windows are subject to change depending on family preference. The following tables and photos display the details of each of the five kitchens from which the team collected data. The team sampled from two traditional kitchens containing no natural ventilation elements, one semi-modified kitchen, and two modified kitchens.

Traditional with Flat Iron Sheet Roof (T-A)

Traditional Kitchen A (T-A) is a relatively small structure with a flat iron roof and single door (Figures 2 and 3). This kitchen has only one small window and contains no roof vent or chimney.

Traditional with Thatched Roof (T-B)

Traditional Kitchen B (T-B) (Figures 4 and 5) has features similar to those of Traditional Kitchen A; however, T-B has a thatched roof. This kitchen contains none of the modified kitchen elements such as a roof vent or chimney.

Volume	Area of Openings	Window(s)	Door	Roof Vent	Chimney
9.24 m^3	1.46 m^2	1	1	No	No

Figures 2 (left) **and 3** (right). Outside and inside photos of Traditional Kitchen A (T-A).

Volume	Area of Openings	Window(s)	Door	Roof Vent	Chimney
8.00 m^3	0.86 m^2	1	1	No	No

Figures 4 (left) **and 5** (right). Outside and inside photos of Traditional Kitchen B (T-B).

Semi-modified Kitchen (S-A)

The Semi-modified Kitchen (S-A) (Figures 6 and 7) is a larger structure that contains more natural ventilation elements than a traditional kitchen, but not as many as a fully modified/clean kitchen. S-A has a roof vent, although partially blocked by a wood drying rack, and an additional window. It does not have a chimney. This kitchen also contains two stoves, which is unlike any of the other kitchens the team analyzed.

Modified Kitchen A (M-A)

Modified Kitchen A (M-A) (Figures 8, 9, and 10) is the largest structure examined. It has three windows, a roof vent, and a chimney, which qualifies it as a fully modified kitchen.

Volume	Area of Openings	Window(s)	Door	Roof Vent	Chimney
21.6 m^3	1.50 m^2	2	1	Yes (partially blocked by wood drying rack)	No

Figures 6 (left) **and 7** (right). Outside and inside photos of Semi-modified Kitchen A (S-A).

Volume	Area of Openings	Window(s)	Door	Roof Vent	Chimney
29.0 m^3	2.03 m^2	3	1	Yes	Yes

Figures 8 (left) **and 9** (right). Outside photos of Modified Kitchen A (M-A).

Figure 10. Photo of stove inside Modified Kitchen A (M-A).

Modified Kitchen B (M-B)

Modified Kitchen B (M-B) is a medium-sized structure with two windows, a roof vent, and a chimney. These elements qualify M-B as a modified kitchen (Figures 11 and 12).

After seven days of collecting the CO concentration in each of the five kitchens described, the team spent time to analyze the data and make comparisons between the kitchens. The data was analyzed using RStudio. To quantify the differences in CO concentrations, several values and plots were generated. First, the raw CO concentration over seven days was plotted. The average CO concentration in each kitchen was recorded. Next, the CO concentrations of T-A and T-B were averaged and compared to the average of the M-A and M-B CO concentrations (excluding S-A). The concentrations in all five kitchens were averaged for a 24-hour period to show the average exposure over one day and also to allow for estimation of the ventilation rate in each kitchen.

In order to calculate the ventilation rate of each kitchen, the 24-hour average carbon monoxide concentration was used. To determine the ventilation rate, an exponential model was fitted to a carbon monoxide decay curve using a linear regression. This decay curve starts from the point each day when the carbon monoxide concentration no longer increases (after the last meal of the day was cooked) and ends when the carbon monoxide concentration has reached 0 ppm. This analysis provides a snapshot in time of the ventilation conditions and may not reflect the true time-dependent ventilation rate throughout the day. An example of this regression analysis is shown in Figure 13 for Modified Kitchen A.

Volume	Area of Openings	Window(s)	Door	Roof Vent	Chimney
17.3 m^3	2.13 m^2	2	1	Yes	Yes

Figures 11 (left) **and 12** (right). Outside photo and stove photo of Modified Kitchen B (M-B).

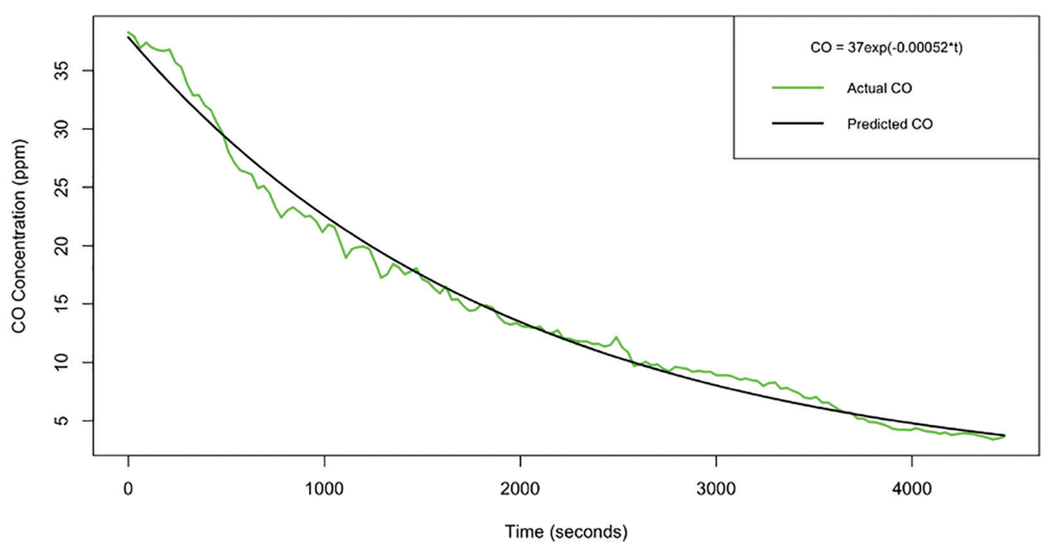

Figure 13. CO decay curve for Modified Kitchen A (M-A).

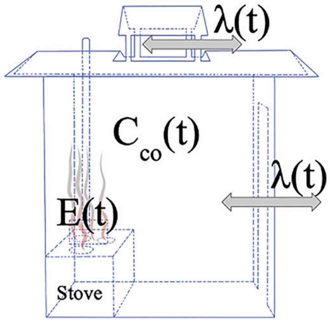

Figure 14. Mass balance model of modified kitchen.

The exponential term (shown in the top right corner of Figure 13) represents the ventilation rate per second of the kitchen. In this case, the ventilation rate is .00052 s^{-1}. The ventilation rate for each kitchen was converted to units of h^{-1} to remain consistent with data that had been previously collected in Nandi.

By obtaining the ventilation rate for each kitchen, the carbon monoxide emission rate of the stove can be calculated. The emission rate of the stove is calculated using the volume of the kitchen, the average carbon monoxide concentration, and the ventilation rate using an equation derived from a mass balance model of a modified kitchen (Figure 14).

The variables used in this model are explained in the following table.

Variable	Meaning
C_{CO}	Concentration of carbon monoxide
λ	Ventilation rate
E	Emission rate
$\forall$	Kitchen volume

The mass balance equation derived from this kitchen model is:

$$\frac{dC_{co}(t)}{dt} = \frac{E(t)}{\forall} - \lambda(t)C_{co}(t)$$

By assuming a pseudo steady-state, the differential term $\frac{dC_{co}(t)}{dt}$ reduces to 0. The equation becomes $0 = \frac{E}{\forall} - \lambda C_o$, and the emission rate can be calculated.

RESULTS

Through the analysis of CO concentration in five kitchens in Nandi, Kenya, GAQT concluded that modified/clean kitchens significantly reduce the amount of pollutants present inside kitchens. Additionally, the team also concluded that the most effective natural ventilation element is a chimney. More details about how these conclusions were made are described below.

Figure 15 shows the concentration of carbon monoxide in each of the five kitchens sampled over an approximately six-day period. The red horizontal lines on the plot show the permissible carbon monoxide levels, as determined by the National Institute of Occupational Safety and Health (NIOSH). The 10-hour time weighted average (TWA) for carbon monoxide exposure is 35 ppm, and the maximum exposure limit for instantaneous exposure is 200 ppm (NIOSH, 1989). As shown on the graph, Traditional Kitchen A, Traditional Kitchen B, and Semi-modified Kitchen A all exceed the 200 ppm instantaneous carbon monoxide limit. Additionally, a significant difference in CO concentrations can be seen between the Traditional Kitchens and the Modified Kitchens.

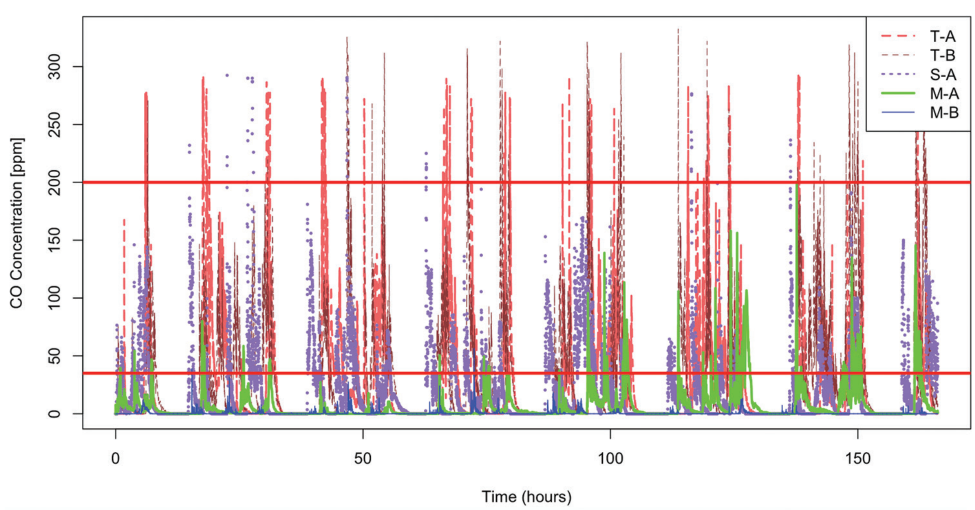

Figure 15. CO concentration in all five kitchens (each a different color on graph) over six days with NIOSH permissible CO concentration limits shown in red horizontal lines.

This plot also shows the difference between each modified kitchen and the semi-modified kitchen. The primary difference in these two types of kitchens is that the semi-modified kitchen does not have a chimney. The average carbon monoxide concentration in the semi-modified kitchen was 30.9 ppm, whereas the average of the two modified kitchens was 4.9 ppm. In this case, simply adding a chimney to the kitchen accounted for an 84% reduction in carbon monoxide concentration.

Figure 16 shows the average carbon monoxide concentration for the traditional and modified kitchens sampled. The semi-modified kitchen was not included in this analysis. Again, there is a significant reduction in carbon monoxide present in the kitchen between the traditional and modified kitchens. The average carbon monoxide concentration during cooking in the traditional kitchens was 42.2 ppm, whereas the average in the modified kitchens was 4.9 ppm. This is an 88% reduction in carbon monoxide concentration between the traditional and modified kitchens.

In order to better understand the daily exposure to carbon monoxide in each of the five kitchens sampled, the carbon monoxide concentration was averaged over each day, and a 24-hour diurnal trend was calculated. This 24-hour diurnal trend is shown in Figure 17 for all five kitchens. Three distinct cooking periods were observed in the kitchens, likely associated with preparation of breakfast, lunch, and dinner.

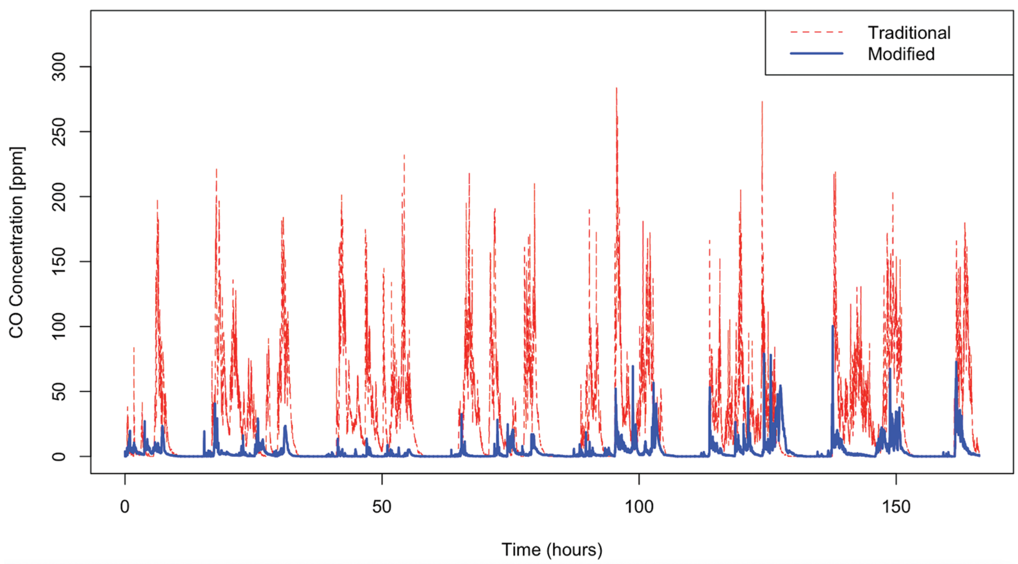

Figure 16. Average CO concentration in traditional and modified kitchens.

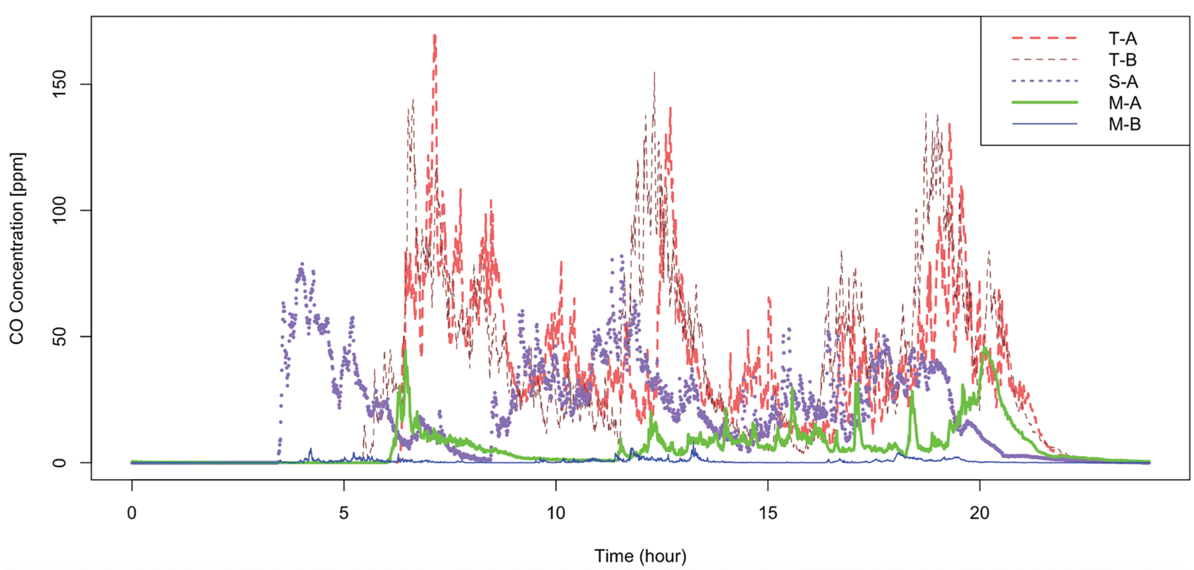

Figure 17. 24-hour diurnal trend in CO concentration in each kitchen.

The results of the ventilation rate estimates described previously are shown in Figure 18.

The results of the calculations for emission rate are summarized in the following table for each kitchen.

The highest emission rate was in the Semi-modified Kitchen, which is expected since this kitchen contained two stoves. The two lowest emission rates were in Modified Kitchen A and Modified Kitchen B, which both had a chimney to remove carbon monoxide straight from the stove to the outdoors. The emission rates for each kitchen are shown in the bar graph in Figure 19. A lower emission rate means that fewer pollutants are emitted from the stove.

Kitchen	Volume [m^3]	Ventilation Rate [1/h]	Average CO [ppm]	Average CO [mg/m^3] *	Emission rate [mg/h] E
T-A	9.24	2.8	49.06	56.2	1454
T-B	8.00	1.8	51.05	58.48	842
M-A	28.97	1.87	10.04	11.5	623
M-B	17.32	4.1	2.54	2.91	207
S-A	21.60	2.1	30.9	35.4	1606

*CO concentrations were converted from units of ppm to units of mg/m^3 in order to calculate emission rate in units of mg/h.

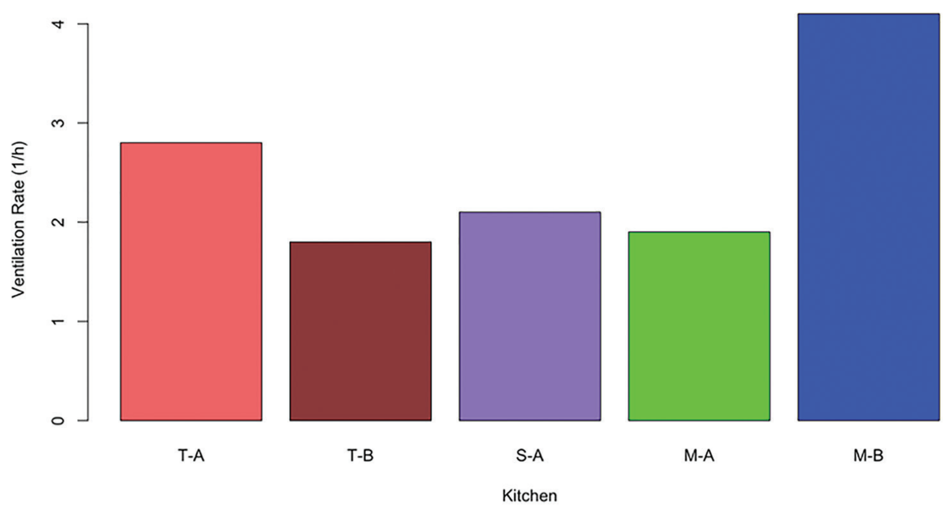

Figure 18. Estimated ventilation rate in each kitchen.

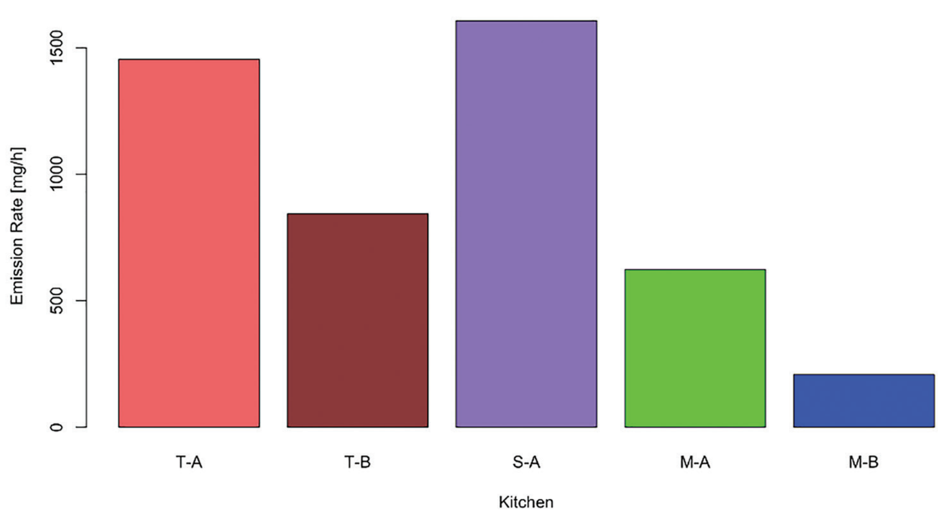

Figure 19. Bar graph showing emission rate in each sampled kitchen.

COMMUNITY IMPACT

By quantifying the difference in indoor air pollutant levels that exist between traditional kitchens and modified kitchens, AMPATH was able to see the value in moving forward with the clean kitchen project. Implementing more modified kitchens in homes in Western Kenya has the potential to improve the health of many women and children in the community. While continuing to build modified kitchens can undoubtedly yield many benefits, there are several barriers to large-scale adoption of the modified designs. Currently, the largest barrier is cost both within AMPATH and for the families in the Nandi community. AMPATH incurs significant costs in ordering and receiving the necessary materials for a new kitchen, and many families cannot afford to purchase these materials. With these challenges, GAQT is looking into ways to make the modified chimney, the most expensive element, cheaper by using different materials and/or redesigning the chimney shape.

Now that the GAQT team has returned from Kenya, AMPATH in Kenya continues to work on the clean kitchen project. The Population Health team within AMPATH has been working to acquire funding to build kitchens as well as introduce the modified designs into other counties in Western Kenya. At Purdue, the GAQT team continues to work within the EPICS program. For the 2019–2020 school year, the team has two design goals, each based on suggestions from AMPATH. The team is currently focused on redesigning the chimney to make it more durable and less expensive. Additionally, the team is developing plans to build a biogas digester, which would provide families in Kenya an alternative to burning biomass fuel in order to cook. In addition to improving the modified kitchen design, the team is investigating the possibility of extending the EPICS program to Moi University, a highly ranked engineering university in Eldoret, Kenya, so that students from Moi University can contribute to the clean kitchen project.

STUDENT IMPACT

The collaboration among Purdue students and their Nandi colleagues has prospered with each stage of the project. Neither party ever imagined the benefits that would come from this project. The community now has five modified kitchens all in different areas across Nandi County. Through building these modified kitchens, the community has developed a clear kitchen design process and trained many individuals as kitchen designers. The Purdue students working on this project have formed a unique skill set on building structures, utilizing sensors to collect meaningful measurements, and analyzing air quality data. Both parties have come to cherish the complexities of international collaborations. Taking time to form these close relationships ensures the benefits of the kitchen design are twofold: mitigating indoor air pollution while preserving the traditional cooking practices within the community.

This project has encountered challenges in various areas including gender roles, funding, cultural norms, and language barriers. Through community gatherings called *barazas*, the team was able to gather a list of challenges the villages are facing with the installment of the modified kitchens. Many women emphasized how important it is for their health and safety to make the switch to modified kitchens. However, in Nandi, husbands typically control their family's finances. This factor, combined with the relatively high costs of installing a modified kitchen, is one of the largest barriers to large-scale adoption of clean kitchens. Additionally, the GAQT team is currently facing a language barrier challenge. The *barazas* were conducted in a mix of Kalenjin and Swahili, so the team only knows the main takeaways from these meetings as told to them by their AMPATH colleagues. However, the team now wishes to translate the audio files from the *barazas* in efforts to address all opinions on indoor air pollution and clean kitchens. Despite these challenges, GAQT, AMPATH, and the Nandi community are working hard to implement clean kitchens in Western Kenya.

CONCLUSION

The clean kitchen design utilized in Nandi, Kenya significantly reduces the amount of pollutants present inside kitchens, and therefore has the potential to improve the health of women and children in the Nandi community. Although the modified kitchen design is completed and effective, there is still work to be done by both AMPATH and the Global Air Quality Trekkers team. GAQT is working on creating a new chimney design that is more durable and affordable as well as exploring the use of solar power as an alternative to biomass fuels. AMPATH is currently evaluating demand for modified kitchens within other counties in Western Kenya. Both AMPATH and GAQT strive to implement these kitchens across Western Kenya and continue to work together toward this goal.

This article aims to provide the reader with an understanding of the scale of the indoor air pollution crisis taking place within developing nations. This problem is widespread across sub-Saharan Africa and has severe health implications for women and children. The article also seeks to illustrate the engineering design process and, specifically, the importance of developing a design that meets the needs of users while not compromising their culture. Additionally, this article highlights the importance of incorporating the different ways of problem solving between two teams across the world, and the success that can stem from cross-cultural collaboration and design.

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